Conceptual Design Optimization of Fighter Trainer Aircraft with Double-delta Wing Configuration

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Abstract: Compared with a delta wing aircraft, the double-delta wing configuration has better aerodynamic performance at high angles of attack. An operational analysis was introduced as a method for evaluating training effectiveness of trainer aircraft. Approaches to the engineering estimation of aerodynamic characteristics for aircraft with a double-delta wing configuration were studied, and the procedures for determining aircraft performance indices formulated. Taking training effectiveness as the objective function and geometric parameters of the wing platform as design variables, through a numerical multivariate optimization arithmetic, the conceptual design optimization for a certain fighter trainer aircraft with double-delta wing configuration was carried out under the constraints of tactical and technical requirements and interrelated geometry. Agreement of a calculation example with engineering practice indicates that the optimal design has higher training effectiveness than the baseline design, and in addition, improves the structural force-bearing conditions.

Key words: trainer; conceptual design; optimization; training effectiveness; double-delta wing

双三角翼布局歼击教练飞机的概念优化设计. 黄俊, M. I. Mostafa, 武哲. 中国航空学报(英文版), 2003, 16(2): 80- 85.

摘　要: 双三角翼气动布局比三角翼飞机具有更好的大攻角空气动力特性。引入了评估教练机训练效能的作战分析法, 研究了双三角机翼布局飞机空气动力特性的工程计算途径以及飞机性能指标的确定方法。以训练效能作为目标函数并选取机翼平面形状的几何参数为设计变量, 采用多变量数值寻优方法, 在战术技术指标及相关几何约束条件下, 对某高级教练机的双三角机翼气动布局方案进行了优化选择。算例表明最优方案不仅比原准方案具有更高的训练效能, 还改善了结构的受力情况, 与工程实践吻合。

关键词: 教练机; 概念设计; 优化; 训练效能; 双三角翼
文章编号: 1000-9361(2003)02-0080-06　　中图分类号: V211.4　　文献标识码: A

Regarded as a complicated engineering system, modern aircraft design is generally divided into three phases: conceptual design, preliminary design and detailed design. The conceptual design is the very beginning and important phase in the aircraft development process, with a feasible optimal design configuration as its objective[1]. An optimized design is a feasible design with optimal performances that closely approximate to their best values under the satisfaction of state equations and constraints. In a traditional aircraft system analysis and synthesis process, a single performance index is generally selected as the objective function, then by using an engineering method for the calculation of constraint and objective functions, the design variables can be optimized. Recently, multidisciplinary design optimization has been widely adopted in the conceptual aircraft design[2].

As the commercial competition and the battlefield environment under high-tech conditions tend to be crueler and crueler, cost-effectiveness, affordability and risk must be considered during the

Received date: 2002-10-31; Revision received date: 2002-12-27
Foundation item: Fan-Zhou Science and Research Foundation
Article URL: http://www.hkxb.net.cn/cja/2003/02/0080/

aircraft conceptual design or making a program decision[3]. Fighter trainer aircraft are employed for the advanced training phase in the training system of an air force. Immense financial resource and manpower should be invested in the development of fighter trainer aircraft. Therefore, government support or international cooperation is the usual approach to the success of this kind of program. Training effectiveness is taken as the objective function in this paper. The design of a fighter trainer aircraft with double-delta wing configuration was optimized with a numerical optimization method called SIMPLEX.

1 Training Effectiveness

In most cases, a flight training procedure can be divided into three different phases: preliminary (screening), basic (intermediate) and advanced training. During a certain training phase, the flying skill mastered by the trainee or student pilot gradually upgrades as the flight training hours increase. It can be seen from Fig. 1 that a training procedure is composed of transient, steady and sat-

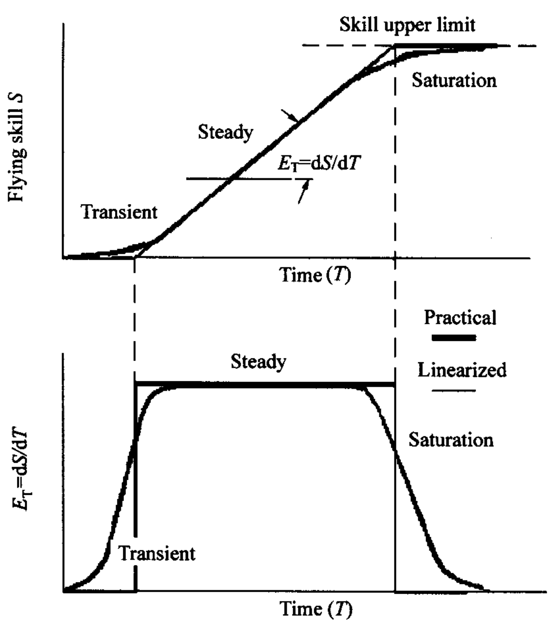

Fig. 1 Definition of training effectiveness for a trainer aircraft

uration sections. The training effectiveness of a trainer aircraft is then defined as the slope of the relation curve between piloting skill (S) and flight training time (T)[4], which is expressed as

$$E_T = \frac{dS}{dT} \tag{1}$$

A method called Operational Analysis is used for the evaluation of training effectiveness, which assumed that the time periods of transient and saturation phases are very short and can be neglected[4]. Only the linear increasing portion of the flying skill as training hours is taken into consideration in this method. Thus a constant training effectiveness value can be drawn out as shown in the lower part of Fig. 1. However, this effectiveness value is a comparison value with that training effectiveness value of a baseline trainer aircraft rather than an absolute one. Operation Analysis method regards the training effectiveness of a trainer aircraft as a function of some aircraft attributes, such as flight performance, flight quality, airborne avionic device and other systems. Flight training program and time period assignment for each training subject are great influence factors to the effectiveness value. Then the E_T can be expressed as

$$E_T = \boldsymbol{Z}^T \boldsymbol{WT} \tag{2}$$

in which $\boldsymbol{Z}$ is the aircraft flight performance column vector composed of maneuverability index, service ceiling, maximum level flight Mach number at sea level, take-off rapidity, landing approach speed, roll performance, gust response characteristics, maximum range at sea level, maximum climb rate and the availability of aircraft mechanical-electro and avionic devices and systems. A whole training mission is generally divided into a certain number of training subjects in a flight program. These subjects include take-off and landing pattern, formation, navigation, night flight, aerobatics, attack, interception, *etc*. For each training subject, a point should be given by some experienced pilots or/and flight drillmasters corresponding to each of the above aircraft attribute indexes to cognize the importance of the index to this training subject. The point consists of 4 ranks: "0" denotes unimportant, "1" general, "2" important and "3" stands for very important. These points build up the weighting factor matrix $\boldsymbol{W}$ in Eq. (2)

after their normalization. $\boldsymbol{T}$ in Eq. (2) is also a column vector with the flight time assigned by the training program for each subject as its element. The main work for evaluating a trainer's effectiveness is to determine the aircraft index vector, which is mainly influenced by aircraft's lift-drag characteristics and the maximum roll moment coefficient. With the baseline trainer aircraft (E_T = 1.0) unchanged during the whole optimization process, the training effectiveness is an absolute value.

2 Engineering Calculation of Aerodynamics for Aircraft with Double-delta Wing Configuration

A double-delta wing aerodynamic configuration can remarkably improve the flow status on the outer wing portion under a high angle of attack, increase lift, reduce induced drag, trim drag and shock wave drag. For this reason, it is adopted by a certain fighter trainer aircraft. To calculate the lift-drag characteristics of the aircraft with double-delta wing configuration, the double-delta wing platform is divided into several straight edge wings: they are inner wing, outer wing, constructed outer wing, base wing and cover wing[5], as shown in Fig. 2.

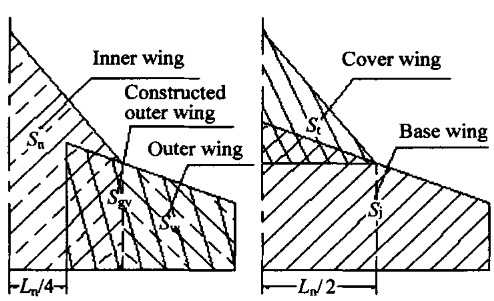

Fig. 2 Geometrical division of double-delta wing platform

The aircraft lift curve slope can be calculated with the following expression

$$C_y^{\alpha} = C_{y\,\mathrm{wing}}^{\alpha}\left(\frac{S_{\mathrm{xps}}}{S_{\mathrm{ref}}}\right)F \qquad (3)$$

where $C_{y\,\mathrm{wing}}^{\alpha}$ denotes the wing lift curve slope; S_{xps} is the exposed wing area which is equal to the wing reference area S_{ref} subtracted by the wing area hidden by the aircraft fuselage; F is the fuselage lift factor. The double-delta wing lift curve slop is calculated based on the area ratio principle. Under subsonic conditions, the lift curve slopes of the constructed outer wing C_{ygw}^{α} and inner wing C_{yn}^{α} are computed first; then the whole wing lift curve slope $C_{y\,\mathrm{wing}}^{\alpha}$ will be

$$C_{y\,\mathrm{wing}}^{\alpha} = \frac{C_{ygw}^{\alpha}S_{yw\,\mathrm{ing}}}{S_{\mathrm{ref}}} + \frac{C_{yn}^{\alpha}S_n}{S_{\mathrm{ref}}} \qquad (4)$$

In the case of supersonic flight conditions, the lift curve slopes of the base wing C_{yj}^{α} and cover wing C_{yt}^{α} are calculated; then $C_{y\,\mathrm{wing}}^{\alpha}$ can be homoplastically expressed as

$$C_{y\,\mathrm{wing}}^{\alpha} = \frac{C_{yj}^{\alpha}S_j}{S_{\mathrm{ref}}} + \frac{C_{yt}^{\alpha}S_t}{S_{\mathrm{ref}}} \qquad (5)$$

Calculation of the wing lift curve slope in the transonic regime ($0.85 < Ma < 1.15$) is very complicated. A predigested engineering method educed from the similarity law was adopted here. After working out the C_y^{α} at $Ma = 1.0$, maximum $C_{y\,\max}^{\alpha}$ and its corresponding Mach number, plus two points of $Ma = 0.85$ and $Ma = 1.15$, the transonic wing lift curve slope can be obtained by using the cubic spline interpolation.

Drag coefficient of an aircraft is composed of zero-lift drag coefficient (C_{x0}) and induced drag. A method called components built-up is adopted for the aircraft zero-lift drag coefficient. According to the area ratio principle, the zero-lift drag coefficient of a double-delta wing can be calculated with the following formula

$$C_{x0\mathrm{wing}} = \frac{C_{x0n}S_n}{S_{\mathrm{ref}}} + \frac{C_{x0w}S_w}{S_{\mathrm{ref}}} \qquad (6)$$

in which C_{x0n} and C_{x0w} are the zero-lift drag coefficients of inner and outer wings respectively. Leading-edge Suction Method is used to compute the induced drag factor[6].

Taking the non-linearity of aileron efficiency and elasticity into consideration, the maximum roll moment coefficient provided by the limit aileron deflection can be calculated with the following expression

$$(m_x)_{\delta_{x\max}} = m_x^{\delta_x}\delta_{x\max} \qquad (7)$$

where $\delta_{x\max}$ is the limit aileron deflection angle; $m_x^{\delta_x}$ is the derivative of aileron efficiency which can be worked out with reference to the baseline aircraft through the comparison method.

3 Determination of Aircraft Performance Index

The aircraft maneuverability index is computed with[4]

$$G = 5\sqrt{2\lambda + 100(t/c) + 10\cos\chi_0 + 10\sqrt{T/W} - (1/25)(W/S)} \qquad (8)$$

where T/W is the aircraft take-off thrust-gravity ratio; W/S the aircraft take-off wing load; λ the aspect ratio; t/c the wing relative thickness and χ_0 the wing leading edge back-sweep angle. The aircraft maximum level flight speed is calculated with

$$Ma_{\max} = \left(\sqrt{\frac{2P_{\max}}{C_x \rho S}}\right) \Big\backslash a \qquad (9)$$

in which $P_{\max}$ is the maximum available engine thrust, C_x the aircraft drag coefficient and a denotes the velocity of sound. The aircraft climb rate is expressed as

$$V_{y\max} = \frac{[(P_{\max} - Q)V]_{\max}}{W} \qquad (10)$$

where Q is the aircraft drag; V the level flight speed and W the aircraft mass with 50% residual fuel. The flight altitude when the aircraft has a capability with the maximum of 5 m/s is called the service ceiling. Given the initial altitude and calculation step, as $|V_{y\max} - 5.0| \leq \epsilon$ is reached, the corresponding flight altitude is the service ceiling. The aircraft gust load incremental coefficient is given by

$$\Delta n = \frac{C_y^{\alpha} K_i K_W \sqrt{\Delta}}{W/S} W_{zs} \qquad (11)$$

where $W_{zs} = 15.25$ m/s is the standard gust; $\Delta = \rho_H/\rho_0$, ρ_H is the atmosphere density at the given altitude and ρ_0 the atmosphere density at sea level; V_i the indicated air speed and K_W the gust alleviation factor. At a constant flight altitude, the aircraft range is calculated by

$$R = \frac{\eta V}{g}\int_{W_2}^{W_1} \frac{K}{q_{kh}} \frac{dW}{W} \qquad (12)$$

in which $W_1 = W - 70$ is the integral upper limit; W_2 the integral lower limit which is the aircraft mass with 7% residual onboard fuel; η the engine effective thrust coefficient; K the aircraft lift-drag ratio and q_{kh} the engine specific fuel consumption. The aircraft take-off time is defined as the period from take-off running to climbing to a safety height of 25 m.

$$\tau = T_1 + T_2 \qquad (13)$$

in which T_1 is the time period of ground running and T_2 the time required for flying to the safety height. The aircraft approach speed is expressed as

$$V_{app} = 1.25 k_1 \sqrt{\frac{2W}{\rho S C_{yjd}}} \qquad (14)$$

where k_1 is the speed correction coefficient; C_{yjd} is the aircraft lift coefficient with flaps fully opened at an angle of attack of $\alpha = 10°$. An aircraft roll performance is expressed as the maximum aircraft roll velocity, which is

$$\omega_{x\max} = 57.3\left|\frac{2V}{l}\frac{(m_x)_{\delta_{x\max}}}{m_x^{\bar{\omega}_x}}\right| \qquad (15)$$

where l is the wing span; $(m_x)_{\delta_{x\max}}$ the maximum roll moment coefficient and $m_x^{\bar{\omega}_x}$ the roll damping coefficient. The availability of systems and avionic devices reflects the number of useful functions the aircraft provides to the pilot. These functions include communication, navigation, weapon delivery, equipment and systems.

As the trainer aircraft attribute index vector (**Z**) is determined, in addition to the normalized weighting factor matrix (**W**) and the flight time assignment vector (**T**), the training effectiveness of a fighter trainer aircraft can be evaluated through Eq. (2).

4 Fighter Trainer Aircraft Design Optimization

A certain fighter trainer aircraft, which is an improved type based on an active trainer aircraft with a delta wing configuration, takes a double-delta wing as its aerodynamic configuration. As the original wing root chord and airfoil keep unchanged, the leading edge back-sweep angle of the inner wing χ_{0n}, leading edge back-sweep angle of the outer wing χ_{0w}, wing span l and wing tip chord b_t were chosen as the design variables in the design optimization problem. These four variables are independent of each other; along with the fixed wing root chord and airfoil, a unique double-delta wing platform shall be determined.

Training effectiveness of this fighter trainer aircraft was chosen as the objective function. Constraint conditions for the optimization were stated as

Half span of inner wing:
$1.98\text{m} \leq L_n/2 \leq 2.94\text{m}$,

Maximum roll velocity: $\omega_{x\max} \leq 560.0°/\text{sec}$,

Approach speed: $V_{app} \leq 330.0\text{km/h}$,

Maximum range at sea level: $R \geq 800.0\text{km}$,

Maximum level flight Mach number at sea level: $Ma_{max} \leq 1.08$,

Gust response coefficient: $\Delta n \leq 0.17\text{s/m}$,

Take-off time period: $\tau \leq 20.0\text{s}$, and

Maneuverability index: $G \leq 25.0$.

Limitations for the design variables were confined as $\chi_{0n} \in (52°, 62°)$, $\chi_{0w} \in (32°, 42°)$, $l \in (7.82, 8.82)$ and $b_t \in (0.63, 1.63)$. Therefore, the aircraft design optimization problem can be expressed as: to seek for an optimal combination of the four design variables, which makes the aircraft training effectiveness the highest under given constraints.

The optimization process was carried out with Simplex Method. Constraint conditions were treated with a punishment method. During the optimization computation, the aircraft take-off weight was calculated with engineering formulations. The data of engine thrust and fuel consumption were treated with double cubic spline interpolation.

Take the prototype trainer aircraft as baseline design, which means its training effectiveness equals one. There is an original design with wing geometrical parameters as $\chi_{0n} = 57°$, $\chi_{0w} = 37°$, $l = 8.32$ m and $b_t = 1.133$ m. The corresponding training effectiveness can be calculated by using Eq. (2), which gives the value of 1.146. The optimization process starts from the original design, *i.e.* the initial values of design variables are the same as those of the original design. After an iterating computation, an optimal design with $\chi_{0n} = 58.50°$, $\chi_{0w} = 37.26°$, $l = 8.18$ m and $b_t = 0.73$ m was finally realized. Based on these parameters, the training effectiveness value of the optimal design is 1.164, which is higher than that of the original design by 1.56%. The historical processes of design variables and training effectiveness during the iteration are shown in Fig. 3.

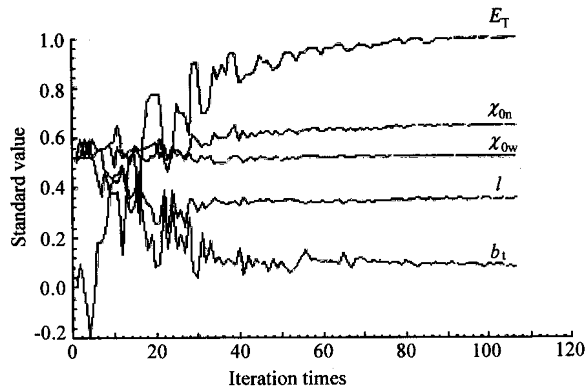

Fig. 3 Historical process of variables and E_T during optimization iteration

The vertical axis in Fig. 3 represents the standardized values of design variables and training effectiveness value. During optimization, the objective function was called on by 107 times, 59 times of which are effective, while the others are invalid due to the value of design variables being beyond their feasible area. Through parameter analysis to the four design variables, it can be believable that the above result is a global optimum solution in the feasible region.

5 Conclusions

(1) Compared with the original design, in addition to the training effectiveness increased, the optimized design has a less-area outer wing, which will help to reduce structure mass and improve stress status of the fuselage force bearing frame. The optimal design is in quite good agreement with engineering practice.

(2) As an integrated evaluation criterion, the training effectiveness being used to assess the design of a fighter trainer aircraft will contribute a positive influence on the market competition capa-

bility of the newly designed trainer.

(3) With simple, easy use and high efficiency as their features, the semi-experiential and semi-theoretical methods were adopted for the analysis of double-delta wing configured aircraft. Through appropriate correction, the calculation precision of these methods can meet the requirements for conceptual aircraft design.

(4) Examination of an optimal design is an issue with challenge. Conducting parameter analysis to each design variable can only upgrade the credibility of the optimal design rather than assure it being a global optimal solution.

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